The Development of Shaped Charges for Oil Well Completion

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ABSTRACT

A new approach to an old problem has made it possible to do in a relatively short period what has not been accomplished in the past three quarters of a century using strictly experimental methods.

A theoretical study was made of the underlying principles whereby a jet is formed by a shaped charge and of the mechanism of the penetration of the target by that jet. It was found that there are more than 10, and perhaps as many as 15 variables affecting the performance of the shaped charge. Only a few calculations are necessary to show that it is physically impossible to investigate all of these variables experimentally.

The shaped charge theory has been extended to include a previously little-understood mechanism in high explosive phenomena; namely, low order detonation. By superimposing a high order detonation on a zone already undergoing low order detonation, an appreciable improvement in performance is accomplished.

The development of a design whereby these phenomena are coordinated in such a way as to develop a jet which is tailored to meet the specific target requirement will be described in detail.

The shortcomings or even impossibility of strictly experimental techniques will be illustrated by a discussion of the development of a special-purpose explosive charge.

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INTRODUCTION

In an article appearing in the May, 1888 issue of *Scribner's Magazine,* Charles E. Monroe described his early experiments with gun cotton (Fig. 1) which led to his name being most frequently connected with our present-day shaped charge. Although the sunken letters or "cavities" in Monroe's gun cotton were not lined, they produced some penetration of an iron plate. The credit for the lined shaped charge, however, should rightfully go to R. W. Wood of the Physics Dept. of Johns Hopkins University, who was responsible for first discovering the fact that a metal liner in a cavity of explosive gave high velocity fragments and/or jets of metal.

This discovery was made by Wood inadvertently while investigating an accidental death resulting from an electric blasting cap. He discovered that a jet of high velocity copper particles was ejected from the dimple

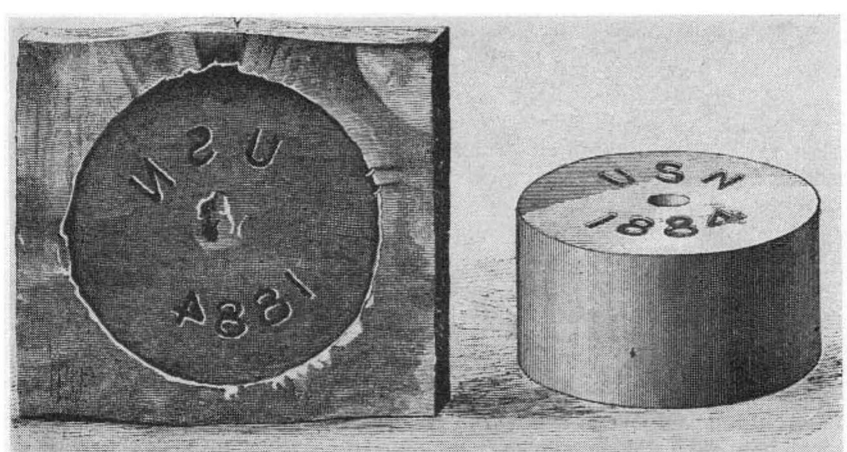

FIG. 1—LETTERS REPRODUCED ON IRON PLATE BY EXPLODING CHARGE OF GUN COTTON WITH SUNKEN LETTERS AS DEMONSTRATION OF MONROE EFFECT.

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pressed into the end of the cap to compress the charge.

This dimple was a recent innovation in the manufacture of blasting caps and arose from the attempt to develop an improved cap. It was already known that a porous, or low density, pressed explosive was much more sensitive to shock than the same explosive pressed to a high density. It was likewise known that the high density explosive, although harder to detonate, was more powerful once it was detonated.

The problem in the electric blasting cap was to develop an explosive load which was sufficiently sensitive that it could be initiated by the small head of primary explosive placed on the filament of the cap and at the same time be sufficiently powerful to initiate the relatively insensitive explosives in common use. A solution was to load the explosive into the cap case in such a way as to result in a maximum density at the bottom of the case, yet with a uniformly decreasing density to the top of the charge nearest the igniter filament. While the desired density gradient could be obtained by packing and pressing the explosive in successive small increments, such a method would be time consuming.

Some ingenious workman got the idea that if the explosive load could first be lightly pressed in the cap case, then, while holding the case stationary, the bottom or closed end of the case could be dimpled, the explosive would be compressed progressively from a maximum density at the dimpled end to a minimum density at the filament end. Tests proved that a cap constructed in this manner gave a superior performance in the initiation of relatively stable explosives. It was assumed that the reason for this improved performance was nothing more than the explosive density gradient which had led to the conception of the idea.

It was not until after Wood's discovery that it was realized that there was any connection between Monroe's work and the dimpled electric blasting cap. As a result of Wood's findings, a very extensive research program was undertaken to develop the lined shaped charge principle into a useful weapon both in this country and abroad.

It has been conservatively estimated that there are more than 10, and perhaps as many as 15, variables which affect the performance of a lined shaped charge. It is necessary to make only a few calculations to show that it is physically impossible to investigate these variables experimentally in all possible combinations and throughout the range of each. In the first place, even if we selected a single size charge requiring only an ounce of explosive it would require more explosive than was consumed in World War I to complete the job, and in the second place it is impossible to change any one of these variables without at the same time changing an unknown number of other variables and by unknown amounts.

ADVANCES IN EXPERIMENTAL TECHNIQUES

Although much work on shaped charges has been done and is continuing on a cut-and-try basis, very little significant progress was made in understanding the mechanism involved in the functioning of the charge and its penetration of the target until the experimental physicist developed such ultra-high-speed instrumentation as the flash X-ray, the smear camera, the raster scope pin technique, and the framing camera, and until he teamed up with the theoretical physicist. This more basic approach has made it possible to develop general principles and a systematic approach in the design of special-purpose charges.

Work on lined shaped charges to date has resulted in the accumulation of such a volume of literature that it now requires over 1,800 IBM cards just to reference the literature with only the briefest of abstracts. Unfortunately, most of this literature is classified, primarily because of the particular items with which it is associated and not because the underlying principles are in themselves considered to be classified. An attempt will therefore be made here to break these principles down into some of the more important phases and analyze their importance in the process of developing a more efficient lined shaped charge for any particular application.

DEVELOPMENT OF A SPECIAL PURPOSE SHAPED CHARGE

The more important of these phases, in order of the sequence in which they take place in a charge as manufactured and fired, are: (1) design of the charge; (2) shaping of the detonation front; (3) transition of the metal liner into a jet; (4) characteristics developed in the jet; (5) penetration of the jet into the target; and (6) characteristics required of the hole in the target.

How to make a charge (Phase 1) and what the end result will be when it is fired (Phase 6) are the only two that are of any concern to most of us, but for the research engineer who must give the manufacturer the design data necessary to produce a charge that will give the desired final result, no one of these phases can be bypassed.

We believe that the most straightforward approach is to start with Phase 6 above and work backward to Phase 1. This can perhaps best be illustrated by outlining a case history of the development, at the Poulter Laboratories of Stanford Research Institute, of an actual special-purpose shaped charge.

REQUIREMENTS—PHASE 6

It was decided that the initial development should be on the basis of a charge for use in a conventional 4-in. hollow carrier for casing perforating. A somewhat arbitrarily selected set of specifications was established for the charge, although these specifications were based on the composite experience of a number of qualified engineers. The requirements were:

1. Explosive weight: maximum of 19 gm to avoid excessive carrier growth.
2. Entrance hole diameter in 5/16-in. thick well casing: ½-in. minimum.
3. Depth of penetration in standard target: maximum possible, preferably 10-in. or more, but at least equivalent to presently available commercial charge.
4. Hole diameter: as large as possible all the way to the bottom.
5. Hole volume: as large as possible.
6. Charge to develop a minimum of slug or carrot to minimize perforation plugging.

PENETRATION OF THE TARGET—PHASE 5

One of the most important factors in the development of a shaped charge is a reproducible target for test purposes. The use of homogeneous targets for the evaluation of a jet which is intended for use on a composite target is meaningless and may be completely misleading.

The mechanism whereby a completely homogeneous target is penetrated is not at all well understood. If, then, we consider a complex target such as is encountered in an oil well, we find that the problem is not too clearly defined to start with. An oil well target generally consists of a port seal (usually aluminum or steel), an unknown thickness of drilling mud, a standard oil well casing, a cement sheath, and then an oil-bearing forma-

tion of not too well known physical properties. A hole of specified characteristics must be made through all of this.

There are many criteria which apply in a very general way to penetration into a target, such as the fact that the degree of penetration by a shaped charge jet is some inverse function of the density of the target or that equal mass of target material produces equal stopping effects. Once the target material is changed (for example, from steel to quartzite) the inverse density ratio may no longer hold. A shaped charge will usually penetrate almost as far into steel as it will into some of the harder rock materials such as quartzite, even though the density of the steel is nearly twice that of the rock.

There is another consideration, namely the hardness of the material, which is an important factor in stopping a jet. Tungsten carbide is probably the most difficult material to penetrate with a jet. These and many other generalizations are useful background material in jet design, but they do not eliminate the necessity of a basic approach to this difficult problem.

Aside from direct examination of the actual hole produced in a target, the most informative technique for evaluating the performance of a lined shaped charge is the flash X-ray. As many as three or four separate flashes can now be made with separate X-ray tubes during the firing of a single charge.

For some work, flash X-ray pictures (or radiographs) of separate shots provide much useful information. Two such pictures (Figs. 2 and 3) show the penetration of a shaped charge into water and through a ⅜-in. steel plate below the water. The first radiograph was taken just before the jet reached the steel plate and the second was taken when the jet had traveled about 1 in. after penetrating the steel plate. It will be observed that the splash of fragments of target metal forms an almost continuous envelope around that portion of the jet which has projected beyond the target. It can be seen, too, that the target metal along the axis of the jet has been given about the same velocity as that portion of the jet which pierced the target.

George E. Duvall[1] has made a theoretical analysis of the penetration of a homogeneous target by means of a jet which takes into account the equation of state of both the material of the target and the jet. On the basis of this limited theory, which takes into account the densities of the material of the jet and the target and the shock pulse velocity and relief wave velocity in each, the size of the hole is related to the mass and velocity of the element of the jet producing it.

[1]References given at end of paper.

Once the specifications for the hole are fixed and the characteristics of the target are known, one can then begin to fix the requirements for the various portions of the jet.

There is a limited number of controls that one can apply to the jet, and one of the most important is the timing of events in such a manner that each element of the jet completes its penetration before the next element arrives.

Characteristics of the Jet—Phase 4

Enough flash X-ray work has now been done with shaped charge jets so that the characteristics of the jet which contribute to good performance have been rather well established. In these studies it has been shown that the following factors contribute to good performance: (1) maximum concentration of the mass along the axis of the jet; (2) straightness of the jet; (3) optimum velocity gradient along the jet with the maximum velocity at the forward tip; (4)

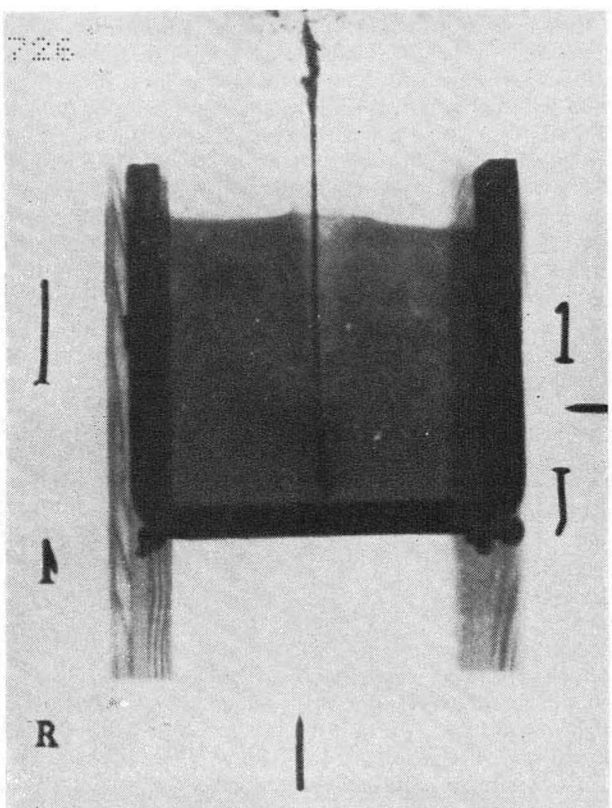

Fig. 2—Flash Radiograph Showing Penetration of Shaped Charge Jet into Water Taken Just Before Jet Reached Steel Plate.

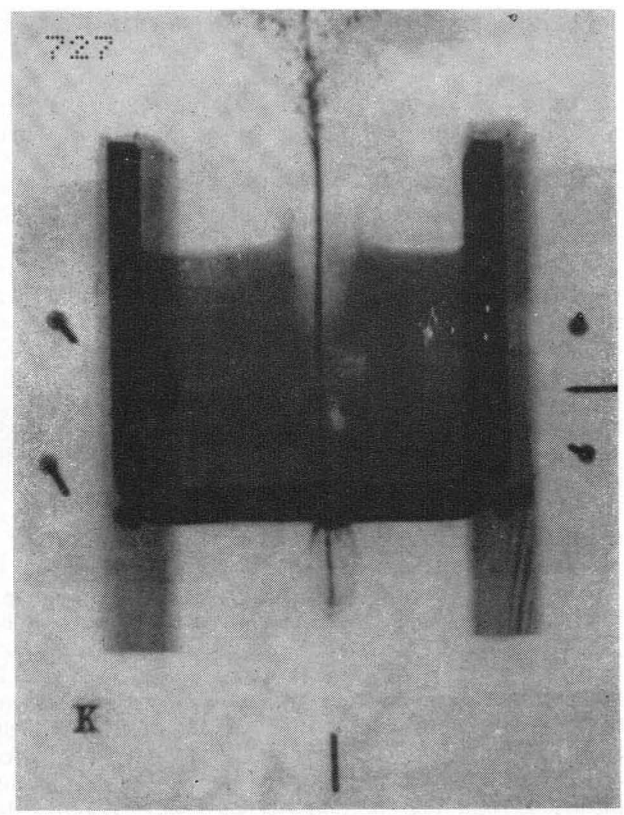

Fig. 3—Flash Radiograph Showing Penetration of Shaped Charge Jet Through ⅜-in. Steel Plate Below Water Taken When Jet Had Traveled About 1 in. after Penetrating the Steel Plate.

maximum over-all velocity consistent with the necessary velocity gradient; and (5) proper distribution of metal along the jet.

Many flash X-ray pictures of good jets show the jet material to be either in a continuous small-diameter rod or a series of short pieces following in line. For a given cone material and jet diameter, this may merely mean a difference in velocity gradient. However useful this breaking up into isolated slugs may be from the standpoint of determining jet velocity and velocity gradient along the jet as determined from flash X-ray pictures, this break-up does not have a chance to occur in normal operation since in general the jet reaches the target before break-up occurs. Even though the jet is in a continuous strand of metal there must be an appreciable velocity gradient along it, with the higher velocity at the forward end. This is necessary in order that each element of the jet will strike the target and accomplish its penetration before the following element strikes.

If the jet is a continuous piece of metal, this merely means that the jet material must not be decelerated as it strikes the target beyond the point where the metal loses all of its elongation and starts to compress and pile upon itself. It is therefore apparent that an excess of velocity gradient will merely shift the point of equilibrium between elongation and compression a little closer to the point of contact of the jet with the bottom of the hole, and will not result in any decrease in penetration except as this may excessively reduce the velocity of the after end of the jet. On the other hand, if the velocity gradient is a little too low, the pile-up of metal in the hole causes the forward end of the jet to be slowed down to such an extent that the jet is continually required to penetrate the piled-up jet material before it reaches the target material at the bottom of the hole.

This is amply illustrated by an experiment in which a minor increase in the density of the explosive around the base of the cone may reduce the penetration by 50 per cent. This slight increase in the density produces an increase in the velocity of the after portion of the jet without changing the velocity of the forward portion, and the jet piles up on itself. If, now, the thickness of the skirt of the cone is increased by only 0.003 in. in a charge having the higher density explosive around that portion of the cone, the original penetration will be restored. In other words, the increased mass compensates for the increased quantity of explosive and the velocity gradient is re-established.

The maximum over-all velocity of the jet consistent with the optimum velocity gradient is, of course, desirable for obtaining maximum penetration. This has been amply demonstrated in a number of military lined shaped charges which are fired from guns or as rocket warheads. If these charges are fired statically or dynamically, maintaining the same rate of spin in both cases, the dynamically fired charge will frequently have an increase in penetration of from 10 per cent to as much as 20 per cent over the statically fired one. In this case, if the dynamically fired charge has a velocity of 2,000 ft/sec when it is detonated, the over-all average velocity of the jet will be 2,000 ft/sec faster than if it were statically fired, but the velocity gradient will remain unchanged. This increase of 2,000 ft/sec in over-all jet velocity will, of course, require a slightly greater velocity gradient, but in those cases where an increase in performance was obtained it is probable that the velocity gradient was slightly more than was required for the static firing.

In some cases, charges dynamically fired have shown no improvement in performance or even a decrease in performance. In such instances it is most likely that the velocity gradient was not great enough for the higher speed. If the velocity gradient were exactly right for static firing, one would expect a reduction in penetration when dynamically fired.

If the distribution of metal along the jet were properly adjusted, it would be possible to produce a hole having almost any profile. The normal velocity gradient combined with a nearly uniform distribution of metal along the jet produces the conventional tapered hole. A large entrance hole, as specified in the requirements, may be produced either by a jet having an extremely high velocity at the forward tip or by one having an increased mass of metal at the forward tip. An analysis of the velocity of the forward tip of the jet of shaped charges already in use showed that it was approaching the theoretical maximum velocity that could be obtained in a jet, or equal to about twice the detonation rate. It therefore appeared to be impractical to attempt to carry this velocity high enough to produce the large entrance hole required. The only other alternative for obtaining a large entrance hole was to increase the mass of metal in the front end of the jet. The specifications selected for the jet which it was believed would meet the requirements were as follows:

1. Size of charge fired.
2. Requirement: entrance hole minimum ½ in. in diameter in 5/16 in. thick steel casing.
   Jet specification: the jet to have 2½ to 3 gm of metal concentrated in a mass at the forward tip or preferably detached from it and having as high a velocity as possible.
3. Requirement: minimum depth of penetration 10-in.
   Jet specification: the remainder of the jet to be concentrated into a solid stream of metal which would elongate into small elements after traveling several inches.
4. Requirement: maximum size hole all the way to the bottom.
   Jet specification: the diameter of the jet to be a minimum directly behind the mass at the front and increase uniformly in diameter with distance from the front.
5. Requirement: hole volume as large as possible.
   Jet specification: same as 4.
6. Requirement: the charge to develop a minimum of slug or carrot to clog the hole.
   Jet specification: slug material to have sufficient velocity gradient to cause it to break up.

That these specifications have been met will be shown in flash radiographs during discussion of Phase 3.

Transition from Cone to Jet—Phase 3

The formation of a jet from a metal cone has been the subject of a great deal of research and some controversy and, as is frequently the case under such circumstances, there is considerable experimental justification even for the most widely divergent points of view. Perhaps the most widely accepted explanation, and one which has more experimental evidence in its support than any other, is the hydrodynamic theory proposed by Pugh[2,3] and his co-workers. The primary reason for the preponderance of experimental evidence in support of this theory is that there are more shaped charges designed in such a way that they are forced to function in the manner described by Pugh, et al.

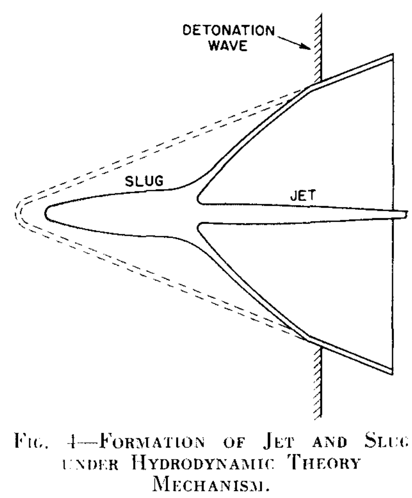

Fig. 4—Formation of Jet and Slug under Hydrodynamic Theory Mechanism.

HYDRODYNAMIC THEORY MECHANISM

This mechanism assumes that the metal of the cone is deflected by the explosive and converges at the axis of the charge (Fig. 4) where it is split, the inner surface of the metal liner being projected forward to form the high velocity jet and the outer surface of the liner being projected backward with respect to the advancing point of convergence along the axis to produce the lower velocity slug. Thus, in such a charge the forward end of the jet comes from the inner surface of the apex of the cone and the after end of the jet from the inner surface of the skirt of the cone.

For the most part, jets which are formed in this manner acquire very little metal from near the apex and an increasing per cent of the thickness of the liner from near the base. It is not particularly difficult to confirm this experimentally by building up a composite cone of different metals or using a truncated cone without reduction in penetration.

PLASTIC FLOW MECHANISM

On the other hand, it is only necessary to make a comparatively minor change in the design of the cone and charge surrounding it to cause a somewhat different mechanism of jet formation to take over. This is a plastic flow mechanism in which the major portion of the forward part of the jet originates from near the base of the cone and the after portion of the jet from the central portion of the cone. This mechanism of jet formation (Figs. 5, 6, and 7) is favored by the use of a comparatively heavy walled small-angle cone and a more nearly uniform explosive thickness over the liner. In the case of this mechanism, the actual cone velocity is lower and the cone collapses throughout its entire length before the tip of the jet emerges from the base of the cone. The much higher mass converging upon the axis, even though at a lower velocity, extrudes the metal along the axis of the collapsed liner, thereby developing the necessary jet velocity and velocity gradient.

Both of the above mechanisms have been demonstrated at the Poulter Laboratories by means of flash X-ray studies and the use of cones constructed of two metals—copper and steel—and penetration into sand. With a loose sand target, the jet material which penetrates any portion of the target is trapped in the immediately adjacent sand. Then by using copper apex and steel base cones (Fig. 8) and steel apex and copper base cones one can determine which sections of the sand were penetrated by steel and which by copper.

SPHERICAL CONVERGENCE MECHANISM

There is still another mechanism of jet formation—spherical convergence (Fig. 9)—in which the liner is a section of a sphere and the detonation front conforms to it and in which the forward portion of the jet originates from the entire inner surface of the liner and the after portion of the jet from the outer surface of the liner, and there is no slug. In this case the diameter of the cone continues to reduce and the thickness increases until it eventually becomes the length of the jet.

BRITTLE FRACTURE MECHANISM

In addition to the above three mechanisms there is the brittle fracture mechanism such as is developed by a liner composed of fused quartz. In the case of a fused quartz liner there is no melting, but the liner is reduced to a powder which forms into a stream of very high velocity, very fine particles. In the case of a glass cone, some melting does occur and the mechanism is quite complex.

There is therefore no single mechanism of jet formation which can be experimentally justified to the exclusion of all others. On the one extreme is the lightweight, conical, wide-angle liner, hydrodynamic theory mechanism in which the forward tip of the jet comes from the apex of the cone, and on the other extreme the small-angle, heavier-walled, plastic flow mechanism in which the forward portion of the jet comes from near the base of the conical liner. Different from either of these is the spherical convergence liner which progressively decreases in diameter and increases in thickness to the point that it forms a long, very small diameter, high velocity rod or jet. (In contrast to the other

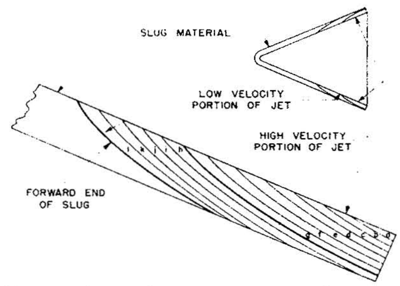

FIG. 5—CROSS SECTION OF CONE SHOWING IN DETAIL THAT PORTION FROM WHICH JET ORIGINATES IN PLASTIC FLOW MECHANISM.

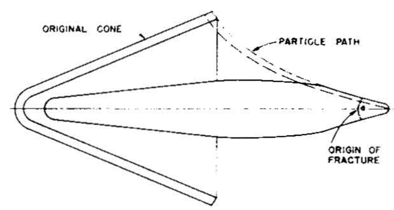

FIG. 6—CONE AT INSTANT OF COMPLETE COLLAPSE AND BEFORE HIGH VELOCITY PORTION OF THE JET HAS BROKEN OFF IN PLASTIC FLOW MECHANISM.

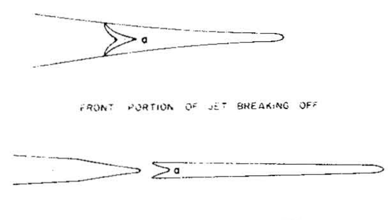

FIG. 7—DEVELOPMENT OF FIRST HIGH VELOCITY PORTION OF JET IN PLASTIC FLOW MECHANISM.

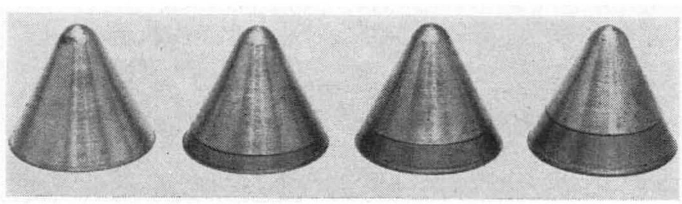

FIG. 8—COMPOSITE COPPER AND STEEL CONES AS USED IN STUDIES OF PLASTIC FLOW MECHANISM.

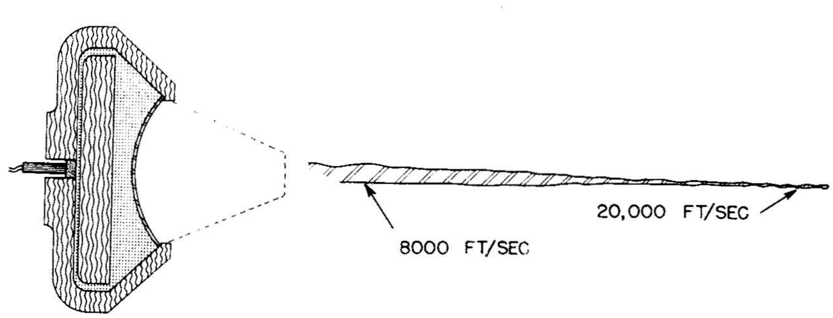

FIG. 9—TYPICAL CHARGE AND JET FORMATION IN SPHERICAL CONVERGENCE MECHANISM.

two, this type of charge does not leave a low velocity slug in the hole.) The brittle fracture mechanism of jet formation is still another type. There are even some charges which may form a part of the jet by one mechanism and the remainder by another.

If we consider that it is possible to have all of these mechanisms, and almost any intermediate modification, it is not surprising that there are so many apparently contradictory data.

With all of these mechanisms of jet formation available, the job of developing a jet with predetermined characteristics becomes both more and less difficult; less difficult because there are so many ways of developing the desired characteristics for each portion of the jet and more difficult because such a small change in design may completely change the character of the jet.

After determining the characteristics for the jet which it was believed would develop the required hole, the problem was therefore to select from the available mechanisms a combination of those which would produce such a jet. It was apparent that no single mechanism of jet formation would meet the jet specifications. A modification of the spherical convergence mechanism seemed to be the only one which could develop the required mass of metal forming the tip of the jet. A liner was therefore designed in which the apex portion was a spherical section, with the hope that a detonation front could be developed which would favor the development of a detached slug rather than an elongated jet. Tangent to, and as an extension of, this spherical section (Fig. 10) was a truncated conical section.

The development of the detonation front will be discussed later but test findings and subsequent flash radiographs confirmed the presence of the detached slug (Fig. 11). However, the hole developed by this jet in a target, although having the required depth of penetration, had too much taper and was too small at the bottom. The conical section of the liner was therefore modified to a section of an ellipsoid of revolution which, it was hoped, would reduce the quantity of metal in the forward portion of the jet and increased it in the after portion. That this was accomplished is shown in flash radiographs in Fig.

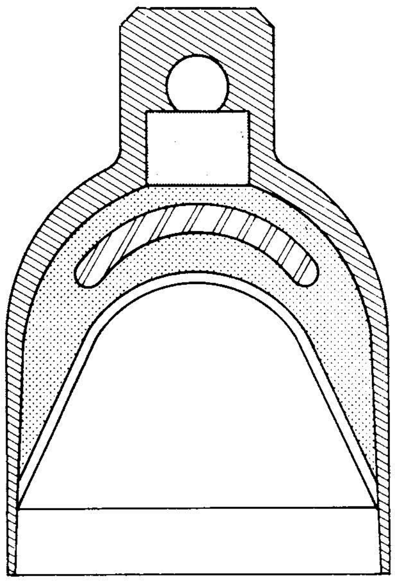

FIG. 10—CHARGE EMPLOYING LINER CONSISTING OF A SPHERICAL APEX SECTION AND TANGENT TRUNCATED CONICAL SECTION.

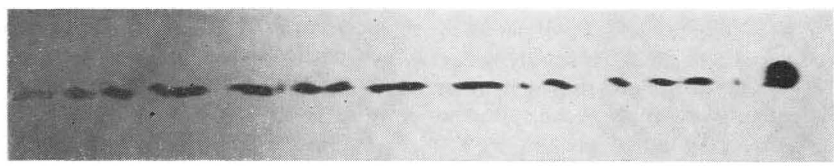

FIG. 11—FLASH RADIOGRAPH CONFIRMING THE FORMATION OF A DETACHED SLUG IN THE JET.

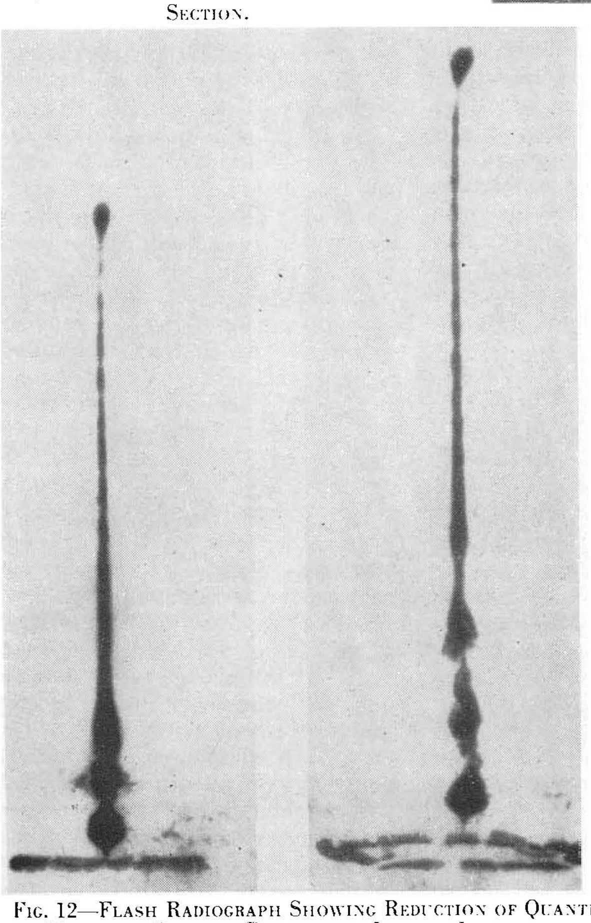

FIG. 12—FLASH RADIOGRAPH SHOWING REDUCTION OF QUANTITY OF METAL IN FORWARD PORTION OF JET AND INCREASE IN THE AFTER POSITION.

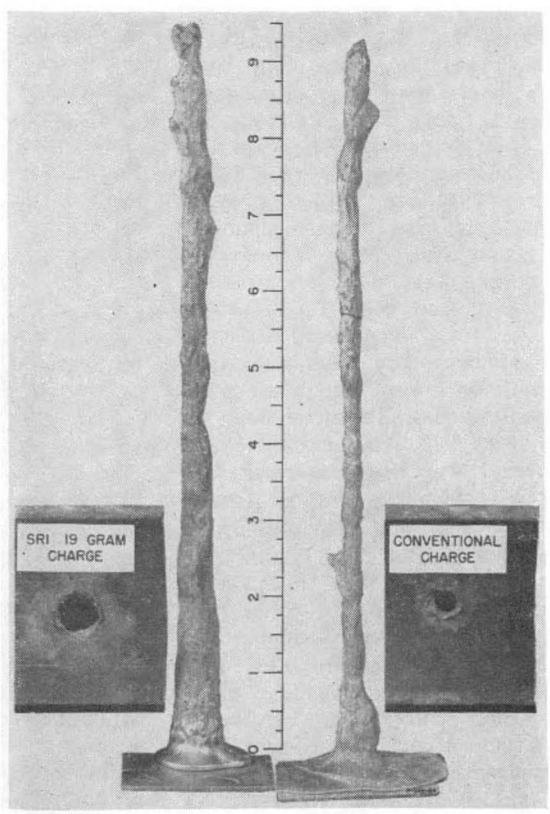

FIG. 13—WOODS METAL CASTS OF HOLES IN TARGETS.

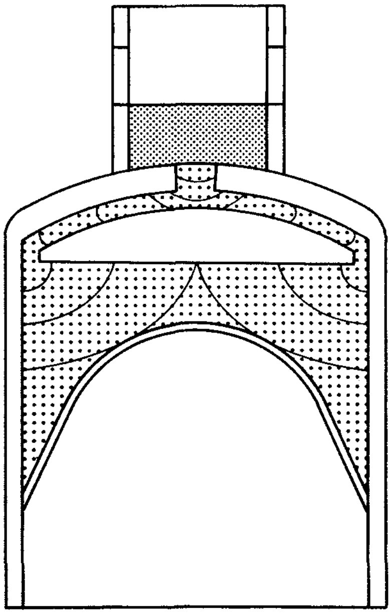

Fig. 14—Development of Detonation Front in Typical Charge Designed for Peripheral Detonation.

12 and the fact that the hole diameter was more nearly uniform throughout its length is shown from woods metal casts of holes in targets, Fig. 13.

The Shaping of the Detonation Front—Phase 2

The number one problem then was to develop sufficiently high velocity in the large mass of metal on the forward tip of the jet so that the following portions of the jet would not overtake it, and at the same time maintain the proper balance between a high average velocity and an optimum velocity gradient. Peripheral detonation (Fig. 14) was investigated and was found to be impractical particularly for the liner as designed for a number of reasons.

1. It tended to increase the quantity of explosive required for good performance.

2. It tended to increase the length of the charge.

3. It necessitated a longer standoff distance for optimum performance.

4. It produced a highly developed slug which tended to follow through and plug the hole.

5. It tended to develop a small-diameter, small-volume hole.

It was also apparent that it would be necessary to take advantage of every available means of imparting a high velocity to that portion of the liner going into the concentrated mass at the forward tip of the jet.

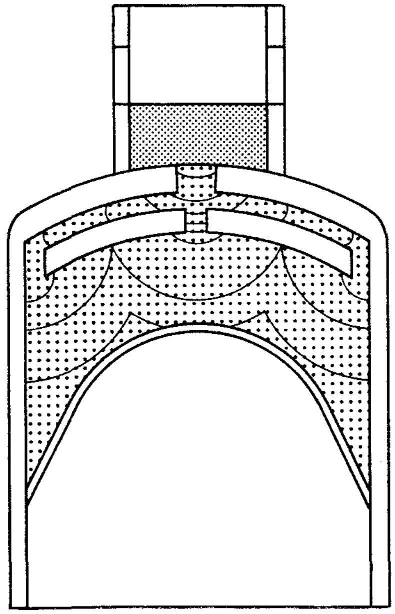

Fig. 15—Development of Detonation Front in Typical Charge Designed to Take Advantage of Extremely High Pressure Developed by Collision of Two High Order Detonation Fronts.

A charge was therefore designed in which an attempt was made to take advantage of the extremely high pressure developed when two high order detonation fronts meet head-on. This was done by introducing a barrier in the explosive charge over the apex of the liner (Fig. 15). A hole was drilled through the center of the barrier. By varying the size of this hole, the high order detonation front being initiated through this hole could be delayed so as to cause it to meet the high order front traveling around the barrier at almost any desired point. However, it was found that the liner would be cut completely through along the line where the two detonation fronts met, thus cutting a circular disc out of the spherical section apex of the liner.

The Design of the Charge—Phase 1

An analysis of the results thus obtained led us to attempt to superimpose a high order and a low order detonation over the spherical portion of the liner (Fig. 16). The shock traveling through the barrier initiates low order detonation in the main charge. This low order is initiated laterally at a high order rate. The high order travels out around the barrier and converges upon the expanding low order. The high order continues on past the low order front and into the low order zone, where only a small per cent of the explosive

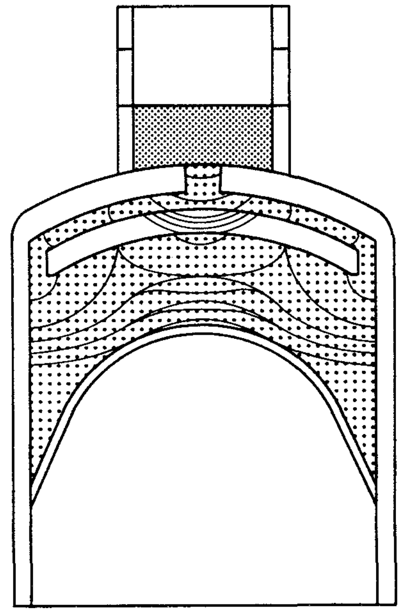

Fig. 16—Development of Detonation Front in Typical Barrier Charge Designed to Superimpose a High Order and Low Order Detonation over the Spherical Portion of the Liner.

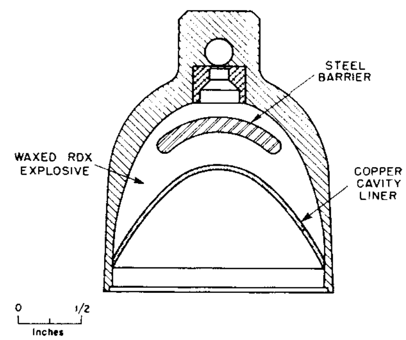

Fig. 17.—Typical Barrier Charge as Developed at Stanford Research Institute.

has reacted. The low order has, however, subjected the unreacted explosive to high temperatures and high pressures, both of which increase its detonation rate, and therefore its detonation pressure, proportional to the square of the detonation rate.

It will be seen from Fig. 12 that the slug which results from such a liner is almost completely disintegrated.

CONCLUSIONS

The charge which was developed as a result of this research program (Fig. 17) has met the specifications initially set up. The entrance hole area was increased fourfold. A slight increase in penetration was achieved. The hole volume was increased about threefold without increasing the total quantity of explosive, and the slug has been virtually eliminated.

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